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AEROENGINE CONDITION MONITORING SYSTEM BASED ON NON-INTERFERENCE DISCRETE-PHASE COMPRESSOR BLADE VIBRATION MEASURING METHOD

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1. INTRODUCTION

There are many different technical engine failures we can face in turbine engine life and exploitation process. The rotor blade fatigue cracks propagation and as a consequence the blade breakaway, the excessive main engine fuel supply and bearing system getting out of order always as a rule cause a formidable danger for flight safety, engine life and reliability.

A detailed analysis each of engine fault occurred during last years in Polish Air force units showed that:

- there were some cases of fatigue blade breakaway in spite of an earlier, check using blade ultrasonic and eddy current defectoscopy and technology,
- there were some cases of bearing system damages in spite of complying with engine maintenance technical requirements,
- the engine fuel system getting out of order was observed as a result of fuel aggregates dynamic characteristics failure of their components as well as exploitation adjustment activities faults caused by deficient adjustment technology or methodology.

Base on above there is of utmost interest the need of looking for new method to recognise stochastic loads during engine operation, their influence on structural engine reliability and running engine technical condition. These methods should comply with present aviation trends i.e. should reduce the number and minimise the weight of control devices as well as reduce the quantity of measured parameters.

The paper presents non-interference technique of turbomachine blade vibration phase method, one of the most interesting such complex jet engine diagnostic method as well as the tool for dynamic phenomena investigation of a running engine. The method is based on discrete blade vibration amplitude measurement and its numerical response analysis referred to the jet engine technical condition analysis [2, 4, 5, 6, 7]. The described method is used in some units of Polish Air Force as SNDŁ-1b/SPŁ-2b SO-3 jet engine diagnostic system. This engine powers polish TS-11 “Iskra” training aircraft.

2. ANALYSIS OF A TURBINE ENGINE MAINTENANCE PROBLEMS IN POLISH AIR FORCE.

About 70% of all faults observed during turbine engine maintenance in Polish Air Force appeared to be located with fuel systems faults or strictly maintenance faults. Turbine engines maintenance monitoring process resulted with conclusion that some of them were caused by external reasons like poor condition of fuel and power supply airfield devices. Some of engine faults originated in pilots engine operating faults relying on not obeying engine warming up and conditioning procedures. Such deficiencies cause as a rule mechanical or thermal low cycle fatigue (LCF). In spite of measurement equipment dynamic development as well as aircrafts providing with flight parameters recorders the expert diagnostic system were not properly elaborated so far in Poland. The reasons of that are many. First there is a little knowledge about the engine construction data specially with Soviet Union origin. Second: there is a lot of discrepancies between the maintenance technical conditions and characteristics and overhall technical conditions.

So far the most popular diagnostic systems are based on MIN – MAX formulae used in stationer machines which states;

If all observed values of all observed parameters are in $<MIN_i, MAX_i>$ range complying with technical maintenance condition requirement it means that engine is fit to fly;

Assumption to this formulae is all observed parameters have no any links and interference between them and controlled object is in constant state of operation. For turbine engine this assumption has to be changed to the following shape;

If all observed values of all observed parameters are in $<MIN_i, MAX_i>$ range complying with technical maintenance condition requirement it means the engine is with high probability is fit to fly.

Paper presented at the RTO AVT Symposium on “Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles”, held in Braunschweig, Germany, 8-11 May 2000, and published in RTO MP-051.

3. DIAGNOSTIC SYSTEM SNDŁ-1b/SPŁ-2b

3.1. Theoretical assumptions of the system.

The consciousness of low plausibility of existing diagnostic systems based on multi engine parameters MIN-MAX control formulae as well as repeated first stage compressor blades fatigue breakaway causes (damages) created the urgent need to elaborate more effective, sensitive system based on minimum quantity of measured and analysed parameters. To solve this complicated problem a qualitative evaluation of applicability of non-contact blades vibration measuring method was done. A particular attention was drawn to the possibility of estimating the condition of a blade (crack initiation and propagation) on a running engine [2] [3]. The measured blades vibration spectrum is analysed using the phase plane. It is worth noticed that such solution enables measurement of rotational speed of the engine rotor by frequency method and the basic difference rely on using the vibrating and rotating blades as a phase marks. This enables to consider measured signal as a composition of two different signals:

- one is a periodic signal of rotational speed (configured by average time value of consecutive rotation of engine rotor),
- second describes oscillation of distance between two adjacent vibrating blades which is stroboscoped by rotational speed.

Basing on narrow band filtering of measured signal we are getting some signal components very useful to expert analysis of engine technical condition following assemblies and structure:

- I compressor stage blades,
- engine fuel system,
- bearing system.

The major concept of expert analysis of engine technical condition is projection of momentary working object characteristics point (i.e. blade, fuel system or bearing system) on phase plane which equals an 3 m – vector of technical state (m – the number of analysed signals).

(1)

$$\forall i \in (1,2,\ldots,m)\;\; WS = \left(par\, , \frac{d\,\mathrm{Pr}_i}{dt}, \frac{d^2 Par_1}{dt^2} \right) \in WT$$

⇨ *ENGINE OPERATIONAL*

In simplest case, having only one analysed signal, for example, engine rotational speed, the working engine range is described in 3 three dimensional space.

The momentary point of engine performance is monitored not only on the transient value of rotational speed but basing on first and second derivative of rotational speed which project some trends of parameters changes (and assisting them excitations).

It can happen that signal Par_i can comply with technical requirement of the engine but first or second derivative will not comply with new widen technical requirement installed during object dynamic characteristics identification process by inverse operation. This case usually projects (the most frequently) the hidden faults of the engine or disadjustment of the particular systems.

The link between engine thermodynamics, fuel system and kinematics describes equation (2). It should be noticed that engine dynamic characteristics identification is based on simply measured signal.

(2)

$$\frac{d^2 n}{dt^2} + a(n)\frac{dn}{dt} + b(n)n = f(m_{pal}, m_{pow}) \approx f(Q_{pal})$$

$$\frac{dn}{dt} = const \frac{M_T - M_S - M_F}{I}$$

Where: n – engine rotational speed,
m_{pal} – mass fuel consumption,
m_{pow} – mass air consumption,
Q_{pal} – volumetric fuel consumption,
M_T – turbine rotational moment,
M_S – compressor rotational moment,
M_F – others assemblies rotational moment

During identification process we were looking for transient function which was describing the linle between technical condition of an engine (characterised by multi-dimensional technical condition vector WS) and measured rotational speed. During engine technical state analysis we employ finite set of phase characteristics points:

TECHNICAL CONDITION =

$$(3)\quad \left(WS\, , \frac{dWS}{dt}, \frac{d^2 WS}{dt^2} \right) \approx \left(n, \frac{dn}{dt}, \frac{d^2 n}{dt^2} \right)_m$$

3.2. Structure of SNDŁ-1b/SPŁ-2b diagnostic system

The system SNDŁ-1b/SPŁ-2b consist of:

- blade excessive vibration signalling device SNDŁ-1b – (fig.1)

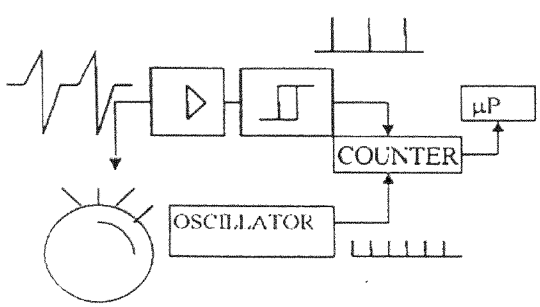

Fig 1. Measurement method

The board device for crew or ground staff warning about dangerous level of blade vibration above 12000 rpm.

- blade crack signalling device SPŁ-2b – (fig.2)

Ground control device for periodic:

a) recording and computer analysis of first compressor stage blade vibration spectrum,
b) SNDŁ-1b technical condition control performance without its disassembly,
c) The engine rotational speed in I and II cabin indicator faults control without their disassembly,

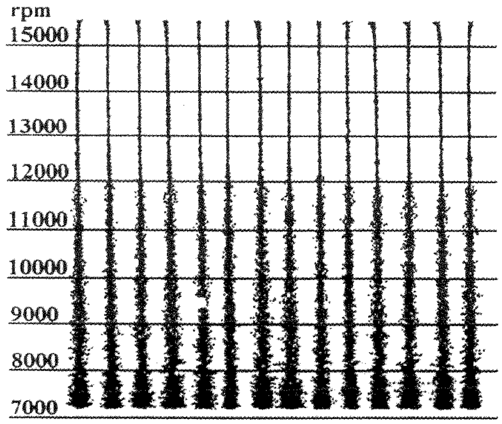

Fig. 2. First stage amplitude – phase compressor blade vibration model spectra of SO-3 engine,

- SPŁ-2b software

Set of specialised procedures for SPŁ-2b numerical maintenance and numerical data analysis, particularly: blade vibration spectra; fuel and bearing system technical condition analysis.

3.3. The functional potentialities of the system
3.3.1 Numeral analysis of blades vibration

The effect of blade upon its numerically analysed by considering the blades as appropriately shaped, beam fixed to the rotor disc (self – likeness condition) in centrifugal force field. An actual flow disturbances level running engine is evaluated by employing the linear dependence of disturbances with vibration amplitude (in elastic deformation range). Numerical procedures employ sectional statistical analysis to get average values of blade vibration amplitudes and standard deviation. The analysis results are compared with the engine type model see fig. 2 and 3.

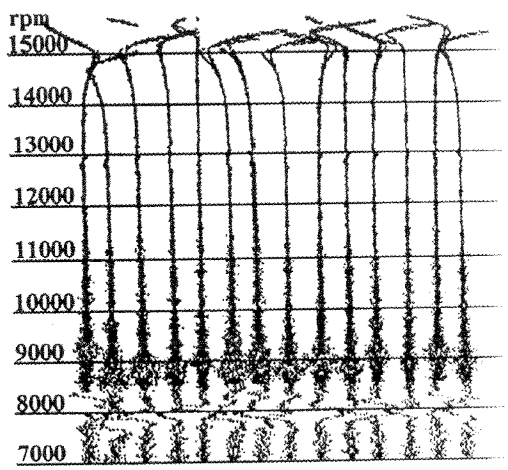

Fig.3. Influence of foreign object dwelling in compressor first stage stator blades on first stage amplitude – phase compressor blade vibration of SO-3 engine

Fig. 2. Introduces projection of first compressor stage amplitude vibration spectrum model of SO-3 engine, fig. 3 – amplitude vibration spectrum during foreign object dwelling on the first stage compressor stator blades. (Y – axis – amplitude of vibration, x-axis rotational speed of the engine). Effect of blade phase resonance characteristic project by low fluctuation of vibration amplitude (in dynamic pitch) was used in numerical procedure. Narrow band filtering of measured signal was implemented with use if aliasing effect in numerical procedure. The core blades technical condition analysis is based on comparing of the engine dynamic pitch projection to the model projection of an engine.

To get explicit identification of crack suspect or suspect blade an numerical procedure was used to estimate blade free vibration frequencies. Narrow band filtering of measured signal was implemented by low square (LS) method.

After blades free vibration frequencies estimation an identification process with factory or overhall basic blades frequencies is following. During test bench investigations the lowering of blades vibration amplitude was observed particularly in blade resonance excitations range. This phenomena is lowering of Q —factor the mechanical narrow band filter which the blade creatures. During cracks propagation process the correction of the blade is decreasing which causes decrease of free vibration frequency “f_s” and blade dynamic frequency factor “B”. During engine run these changes project in decreasing of blades forced vibration frequencies "“$_d$” –Fig fig. 4 (y-axis – dynamic pitch phase, x-axis rotational speed). For first compressor stage blades of SO-3 engine the dynamic changes were the most distinct near maximum of rotational speed of the engine in which the second synchronous excitation of resonance vibration occurs – fig. 5 (y-axis rotational speed, x-axis synchronous component of vibration amplitude phase change).

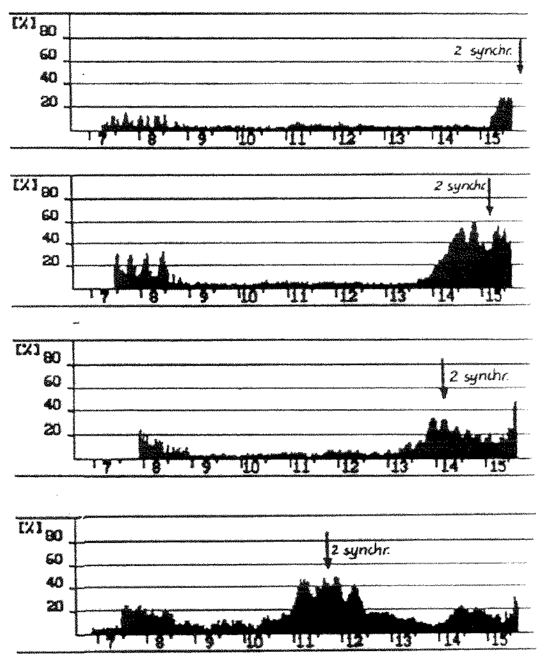

Fig. 4 Projection of blade crack propagation process in blade phase vibration spectra.

3.3.2. Numeral analysis of dynamic load of engine rotor bearings

Blades amplitude and vibration frequency data having got during numerical analysis of all rotor blades were used for identification of some disadvantageous dynamic phenomena time to time occurred during engine exploitation process. For this numerical procedure gives relation between:

- bearing system technical state and blade load effect,
- blade characteristic vibration and bearings dynamic load level.

Procedure has sufficient sensitivity for revealing such phenomena like synchronous and asynchronous rotor blades resonance vibration – fig. 5.

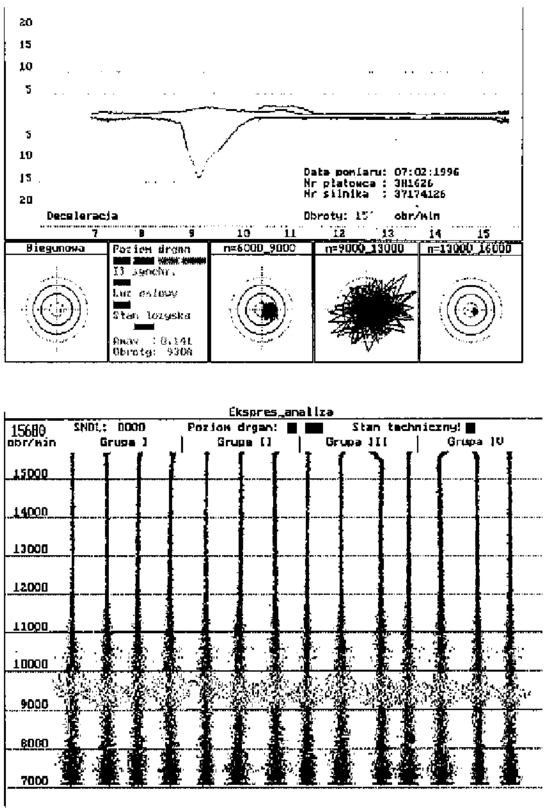

Fig. 5 Influence of blades vibration on the rotor dynamic conventional disbalance level

The results of the analysis are projected conventionally in the shape of normalised radius and dynamic rotor unbalance phase (y-axis-engine rotational speed, x-axis – conventional, normalised dynamic unbalance radius).

3.3.3. Technical estimation of fuel system condition

Big frequency of sampling of the rotational speed of the engine (once for each rotor turn allows in very simple way to possess information concerning transient value of rotational speed. Having in view relations-between engine fuel consumption and rotational speed (related to real atmospheric weather conditions) an numerical procedure for fuel system technical conditioned estimation was elaborated. Procedure compares real dynamic characteristic taken during non stabilised range of engine operation (acceleration and deceleration) with

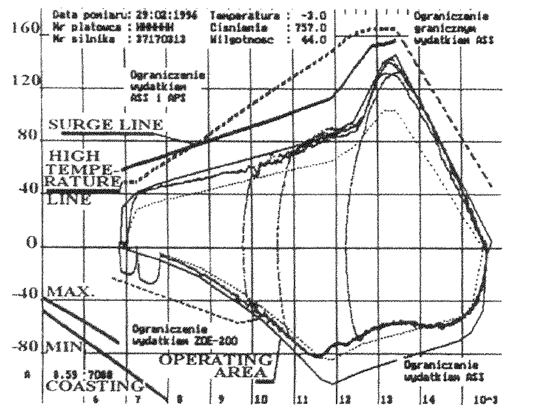

Fig. 6. Model characteristic of engine fuel system during transient condition of SO-3

model dynamic characteristics – fig. 6 (Y-axis – engine rotational increase of rotational speed). Having in view structure and principles of the engine fuel system work, procedure allows:

- all fuel system aggregates and the whole fuel system adjustment and control – fig. 7;
- early revealing of engine fuel system and fuel aggregates failures – fig. 8.

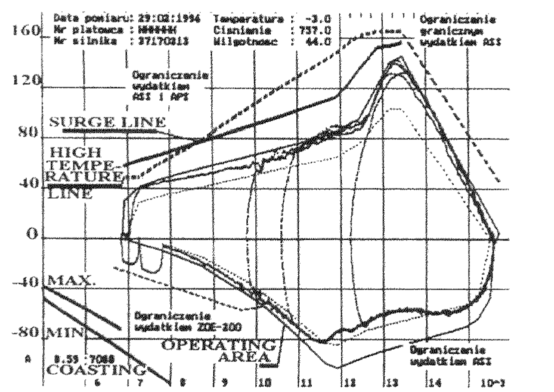

Fig. 7. The presentation of improper engine acceleration time adjustment – reduction of the margins of compressor stability (surge threat)

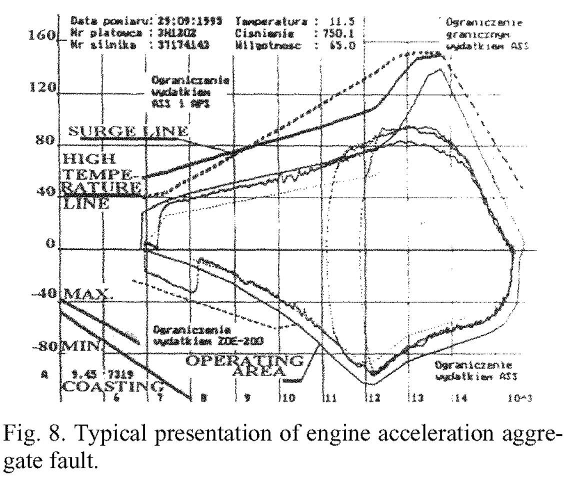

Fig. 8. Typical presentation of engine acceleration aggregate fault.

4. CONCLUSIONS

1. Described method is of great importance for flight safety and may be recommended as a completion of the existing systems of diagnostic of turbine engines.
2. By using the discrete, non-contact method of measuring blades vibration and numerical analysis of blade vibration spectrum it is possible to conduct complex, monitoring of technical state of major engine components like:
- compressor blades
- fuel system
- bearing system.

REFERENCES

1. Kudelski R., Szczepanik R. *Urządzenie do bezdotykowego wyznaczania amplitudy drgań w łopatkach sprężarki silników lotniczych*, V KNT "Metody pomiarowe w technice lotniczej", ITWL Warszawa 1987.

2. Szczepanik R. *Analiza i badanie przyczyn urywania się łopatek I stopnia sprężarki silników SO-3/SO-3W.* Sprawozdanie ITWL Warszawa 1987 (nie publikowana).

3. Szczepanik R. Badanie stanu drgań i naprężeń w łopatkach I stopnia sprężarki silników typu SO-3 w eksploatacji. Sprawozdanie ITWL Warszawa 1988 (nie publikowana).

4. Szczepanik R., Witoś M. *Quality Assessment of Diagnostic Non-Interference Discrete-Phase Method of Measuring Compressor Blades Vibration*, XIX Konferencja ICAS Anheim 1994.

5. Szczepanik R., Witoś M. *Wpływ procesu eksploatacji turbinowego silnika odrzutowego na żywotność łopatek wirnikowych*, VII KNT Przepływowe Maszyny Wirnikowe, Rzeszów 1993.

6. Szczepanik R., Witoś M. *Computer Aided Engine Condition System based on non-interference discrete phase blade vibration measuring method, SAE/SAS*, Symposium/Workshop Stockholm 1995.

7. Szczepankowski A., Witoś M. *Obiektywna kontrola stanu technicznego układu paliwowego turbinowego silnika odrzutowego typu SO-3 (SO-3, SO-3W, SO-3W22)*, Konferencja DIAG 95 Szczyrk 1995.

8. Szczepankowski A., Witoś. *Wpływ stanu technicznego układu paliwowego turbinowego silnika odrzutowego na drgania łopatek wirnikowych sprężarki*, Konferencja DIAG 95 Szczyrk 1995.

9. Witoś M. *Bezdotykowa metoda kontroli stanu technicznego łopatek wirnikowych sprężarki osiowej*, Konferencja DIAG 95 Szczyrk 1995.

10. H.Dąbrowski,R.Kudelski, J.Spychała, R.Szczepanik, A.Szczepankowski, M.Witoś.Turbojet Engine Diagnostic System Based on Compressor Blade Vibration and Vibroacoustic Analysis. XX Konferencja ICAS, Sorento, 1996.

11. R.Szczepanik, M.Witoś. Komputerowy system diagnostyczny silników odrzutowych bazujacy na dyskretno-fazowej metodzie pomiaru drgań łopatek. Zeszyty Naukowe Instytutu Lotnictwa Nr 152/1/1998.

PAPER -13, R. Szczepanik

Question (H. Weyer, Germany)

Blade vibration is often flow-triggered. Have you tried to actively control the vibration by flow management using the monitoring system?

Reply

Yes, but not directly by the adjustment of the fuel system. We noticed in an early stage of our work that there is a strong link between the adjustment quality of the fuel system and the level of blade vibration. So with time we significantly reduced the level of blade vibration by proper adjustment of the fuel system of individual engines. The nine year period of exploration of our diagnostic system without engine damage provides strong evidence of the success of this approach.